JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

IMPLEMENTATION OF PCM IN COMMERCIAL BUILDINGS ENVELOPE IN EGYPT

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Abstract: Nowadays, new commercial building envelopes are seeking to reach sustainable design standards and codes worldwide. However, buildings in hot climates poorly adapt to external environmental conditions. The building envelope plays a major role in the outdoor and indoor environment. An appropriate indoor thermal condition in buildings is important because of the building occupant's comfort. This paper tests the effect of building envelope using Phase Change Material on the HVAC energy consumption and thermal performance of medium office buildings in Cairo using the Design Builder simulation tool. The model external building envelope is designed according to the Egyptian code and the model building of a medium office on design builder follows the ASHRAE standards. The model building envelope uses the same PCM material in different building allocations to test the effect of PCM on the building envelope on the indoor thermal comfort and energy consumed.

Keywords: Commercial building envelope, Heat storage, PCM, HVAC consumption, unmet hours, Design builder simulation.

1. Introduction

Egypt now is going through a development path trying to overcome the energy crisis with the limited amount of energy resources and increasing demand. According to the rapid development of the country it is expected that the energy crisis come worse in the next few years, this mainly includes the building sector. More than 60% of the electrical energy is consumed by the existing building stock. Considering the building envelope in design, using efficient materials to adapt better to the external environmental conditions and altering the occupants' behavior concerning energy usage, are the main factors that improve the energy performance of buildings[1]. The energy usage of air conditioning is quickly increasing in order to create a comfortable interior thermal environment, which has severe consequences for sustainable development. To address the issue, passive low-energy structures have been designed[2]. Improving the thermal performance of the building envelope is a good way to produce a consistent internal temperature and lower building energy usage [3]. A way to improve building envelope thermal performance is to increase building thermal inertia in order to improve resilience to changes in the outdoor thermal environment [4][5], especially in climates with a large daily temperature range, where improved building thermal stability could result in outstanding energy efficiency performance [6][7].

2. Building envelope

Many of a building's exterior elements, such as walls, roofing, foundations, windows, and doors, are included in the building envelope[8]. It contains all elements that make up the building's shell or skin as shown in **Error! Reference source not found.** . Any living space with heat or air conditioning will be included and have an effect on the rest of the buildings, especially in terms of climate, ventilation, and energy consumption[9]. The building envelope has four primary purposes. Adding structural support, managing moisture and humidity, regulating temperature, and controlling air pressure changes are only a few of the options. The envelope influences ventilation and energy usage inside the building by serving. heating, cooling, and ventilation[10].
According to the US Department of Energy, the building envelope loses 42% of the energy used by nonresidential buildings in the United States. When designing an energy management plan, this highlights the importance of focusing on the building envelope. The aim is to construct an airtight and well-insulated envelope that allows the energy that enters the building while keeping it in the envelope, and any outside weather conditions has a little effect on the indoor comfort [11].

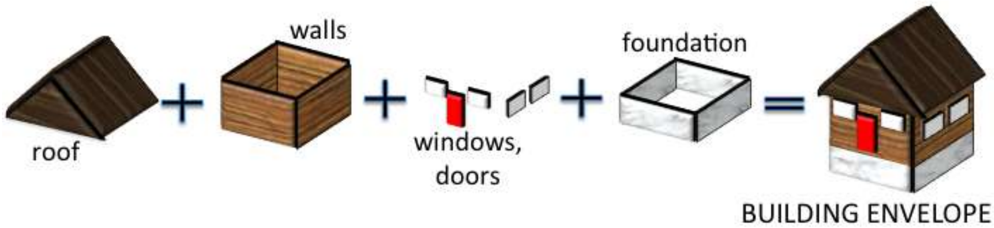


Figure 2-1 Building envelope components [9]

2.1. Energy code for Commercial Buildings in Egypt

The new constructed buildings should fulfil energy efficiency requirements as a whole building. The Egyptian code for energy of commercial buildings stated some requirements for building envelope design to improve energy use and offer thermal comfort for occupants using the building. The following Table 2.1-1

Table 2.1-1 is the code recommendations for building envelope design for conditioned commercial building envelope requirements for Delta and Cairo [12].
In case of inserting insulation in the internal side of the wall construction, the thermal resistance decreases by 30%. The unventilated 100mm airgap thermal resistance reaches 0.16 W/m2 0C [12].

Building characteristics	***Description***	*Medium office building*
	Area	*4,982m^2*
	Form	*Rectangle*
	Number of stories	*3*
	Height	*11.7m*
Operation (schedules)	***occupancy***	*8:00am-06:00pm*
	operation	*8:00am-06:00pm*
	Days	*Sunday-Thursday (According to Egypt holidays)*
Building envelope material	***Wall building material***	*2cm Mortar out + 25cmBricks + 2cm Mortar in*
	Wall R value	*R=0.60*
	Roof building material	*12cm reinforced concrete+ 8 cm inclined reinforcement+ 2cm extended polystyrene+ 6cm sand+ 2cm mortar+ 2cm tiles*
	Roof R value	*R=0.99*
	Air gap	*4mm-6mm*
openings	***Window percentage***	*33%*
	Material	*Double glazed*
	Building envelope vents (elevation)	*When using air gap:* *Vertical spacing 6m* *Horizontal spacing 4m*
Light	***Density***	*12-16 /m^2*

Table 2.1-1 Building envelope design requirements [12]

2.2. Building envelope ventilation

The building envelope should be well ventilated to meet the code standards. Due to building envelope high potential for increasing building thermal performance, air layer involved envelopes (ALIEs) have gained considerable importance in modern building design and construction. Essentially, the air layer serves as an extra layer of insulation or a ventilation route[13]. The Egyptian code advise with an air gap between 40-60 mm, that is needed to release the heat between the layers and allows air movement as shown in Figure 2.2-1.

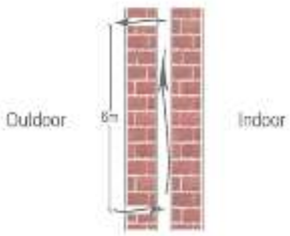


Figure 2.2-1 Building envelope ventilation [12]

3. Phase Change Material

The investigation of Phase Change Material PCM for applications for heating and cooling in building mass has a long history. Already in the 1930s, M. Telkes investigated the use of PCM to store solar heat and use it for space heating. After the oil crisis in 1973 other researchers continued these investigations. However, applications were not yet economical. In the past decade, the situation has started to change because of rising energy prices. The energy demand to ensure indoor thermal comfort has increased worldwide, especially the demand for cooling and air-conditioning[14].

Improving the thermal performance of the building envelope is a significant technique to reduce the amount of energy used by the structure. The phase change energy storage building envelope aids in the efficient use of renewable energy, the reduction of building operating energy consumption, the increase of building thermal comfort, and the reduction of pollutants and greenhouse gas emissions in the environment [15].

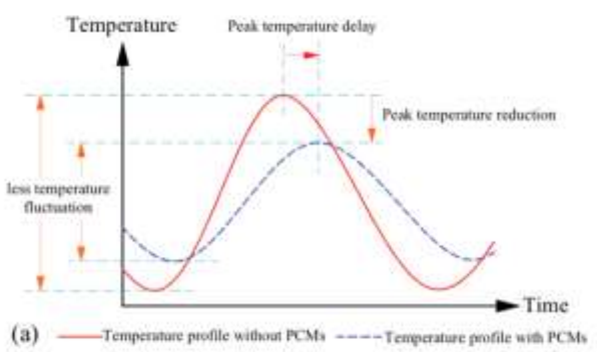


Figure 3-2 Peak temperature difference using PCM [16]

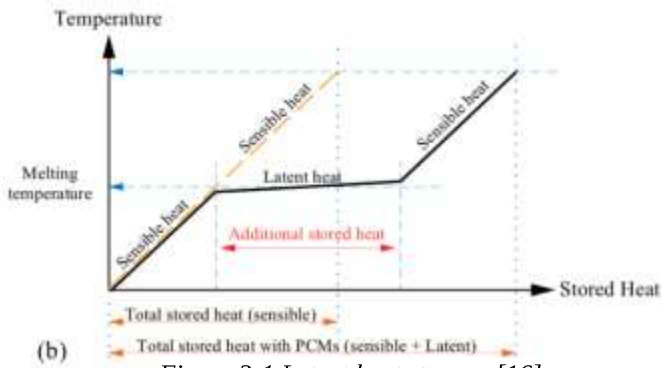


Figure 3-1 Latent heat storage [16]

People like to have room temperatures in a very narrow temperature range. In this case PCM can be used to control the temperature swings or for energy storage with high storage density. It can reduce peaks in demand by creating a more even load-time characteristic as shown in Figure 3-2[16].

Especially in buildings with low thermal mass, the temperature can change significantly very quickly and therefore create an uncomfortable environment. Therefore, applications for heating and cooling in buildings are expected to have large market potential for phase change materials.PCM is latent heat storage material that absorbs heat ash shown in Figure 3-3. Phase change materials are organic compounds or inorganic salts with variable environmental criteria in selecting them, and they both depend on molecular effects. Therefore it is not surprising that materials within one material class behave similar[17] .

3.1. PCM in hot climate building envelope

Over 200 compositions, organic and inorganic compounds, eutectics, and other mixtures have been considered as promising PCMs. A classification of the substances used for thermal energy storage was given by [18] . The major three types of PCMs utilised in building wall applications are classified based on their chemical makeup as shown in Figure 3.1-2 [19]. The most essential feature of PCMs is their enormous heat storage capacity, which is many times more than that of typical building materials like concrete per unit thickness as shown inFigure 3.1-1.The use frequency of different types PCMs in different areas worldwide. It has some representativeness, even though there are certain limits. Direct incorporation, immersion, shape-stabilization, and encapsulation are all methods for incorporating PCM into construction materials and elements[20]. According to **Error! Reference source not found.** Egypt is classified as Tropical desert climate and may use organic PCM for a better performance.

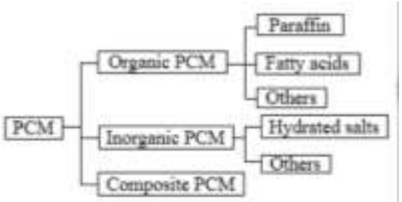


Figure 3.1-1 Classification of PCM [20]

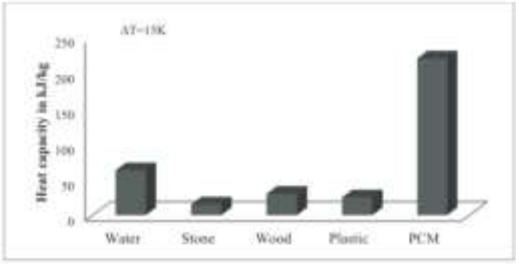


Figure 3.1-2 Heat storage capacity by materials with the same volume [19]

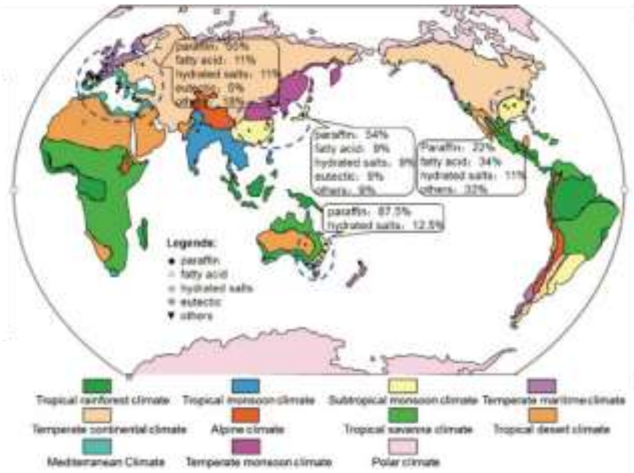


Figure 3.1-3 The use frequency of different types of PCMs indifferent areas worldwide [20]

3.2. Layering PCM

Position of PCM is really challenging and One of the first works dedicated to find the optimal location of PCM layer in an external building wall was done experimentally by Jin et al. in 2013 the application of PCM in external layers of building envelope becomes more and more popular and attractive solution[21]. According to the previous researches, macro-encapsulated PCM could be found in three places in walls: the inner section, the outer part, and the middle. It was discovered that by strategically placing a PCM layer between the outer side of the brick and the plaster layer in the exterior wall, more than 28% of energy was saved. In the other parametric study of PCM location, It was suggested to locate PCM near the external surface utilising an air gap and insulation [22]. PCM thickness and its location in the building envelope is a very debatable matter. This because the PCM is a special material that responds to where it is used and how. Different researches were made previously and each has different outputs according to weather conditions, type of Pcm, specifications of PCM, other building materials and their allocations and other factors [23].

4. Experimental scheme

A simulated building model for medium office in Cairo using PCM in the building envelope is carried out to test how sensitive the model is to the PCM material as a first simulation and compare it to the conventional building envelope according to the Egyptian Code to Improve Energy Efficiency. The model moves forward to simulate the PCM material with different building envelope location to reach a better building envelope resistance with a good Thermal comfort. The model use Cairo, Egypt weather data.

4.1. Building form

Building simulation form of office building has a stated standards from ASHRAE for of a medium office building that defines the size, form and interior spacing specifications to be modeled for testing as shown in Table 0-1 . The model building envelope follows the Egyptian Code to Improve Energy Efficiency. The building orientation is toward North.

Table 0-1 Medium office building

Item	**Rectangle building**
Building type	Medium office building
Location	Cairo, Egypt
Perspective	
Number of stories	3
Floor area	$35m x 45m = 1575m^2$
Floor height	4m

4.2. HVAC settings

This section describes the HVAC specifications and sizing setup used in the design builder model. The model of HVAC system is assembled by distributing a defined amount of water and air in the loops together with a group of zones when connected they form a complete system. The system used in design builder operates in a simple mode, which is turned on all weekdays and turned off at the weekends. During weekdays it works from 08:00 to 18:00 from Sunday to Thursday. The heating and cooling setpoint temperatures are the minimum of fresh air per person and illuminance needed, which is related to the zone activity or how it is. Used. Table 4.2-1 below shows the heating and cooling set point used in the model. Table 4.2-2 show the design conditions for HVAC sizing in the proposed model.

Table 4.2-1 HVAC system

System	**VAV, Air-cooled Chiller, Steam humidifer, Air-side HR, Outdoor air reset**
Heating/cooling	Electricity from Grid
Heating Setpoint/Setback	22.0/ 12.0

Cooling Setpoint/Setback	24.0/ 28.0
Cooling COP	3

Table 4.2-2 Design conditions of HVAC sizing days

	Heating conditions	**Cooling conditions**						
Date used	**January 15**	**21 April**	**21 May**	**21 June**	**21 July**	**21 August**	**21 Sep.**	**21 Oct.**
Day type	Sunday/ holiday							
Dry-bulb temperature (°C)	2	38.8	40.4	40.8	39.8	37.9	38.7	36.1
Wet-bulb temperature (°C)	2	18.6	20	21.4	22.4	23.7	21.7	20.9
Daily dry-bulb temperature range (°C)	0°C	16.4	15.9	14.5	12.8	11.7	12.4	11.9
Windspeed/ direction (m/s, °)	11.2, 0	0, 0						
Solar	ASHRAE clear sky with 0.0 clearness	ASHRAE clear sky with 1.0 clearness						

4.3. Activity profile

The activity profiles used for different space functions during weekdays and weekends. The activity profiles and values are obtained from ASHRAE 55-standards that are represented in metabolic rate, number of occupants per space, lighting power density, and equipment power density as shown in

Table 4.3-1.The occupancy density people/ m^2 =0.1110, Metabolic Rate (Men=1.0, Women=0.85, Children 0.75). The clothing is set in winter to be 1 and summer 0.5. The office equipment are 100% working according to the operating hours and schedules and 50% at the rest of time excluding weekends which is totally switched off as shown in Figure 4.3-1.

Open Office Space	
Weekdays	**Weekends**
Metabolic Rate W/Person	0.90
Occupancy Density people/m^2	0.1110
Lighting power density	15.00 W/m^2
Lighting power density	15.00 W/m^2
Office equipment setting	11.77 W/m^2
Equipment power density	30 W/m^2

Table 4.3-1Open office space schedules

Open Office Space	
Weekdays	**Weekends**
Metabolic Rate W/Person	0.90
Occupancy Density people/m^2	0.1110
Lighting power density	15.00 W/m^2
Lighting power density	15.00 W/m^2
Office equipment setting	11.77 W/m^2
Equipment power density	30 W/m^2

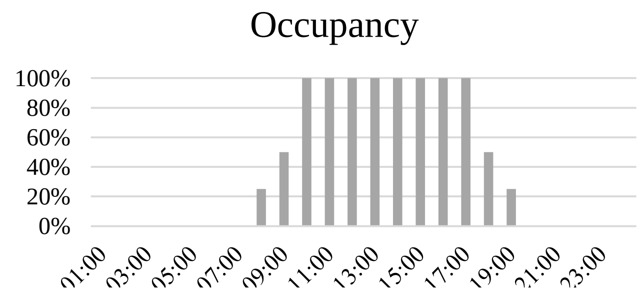
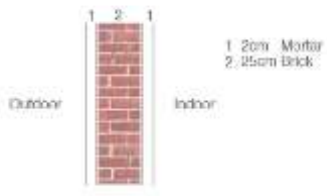
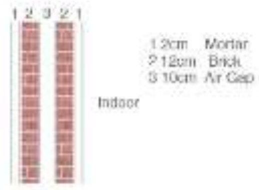
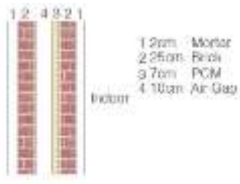
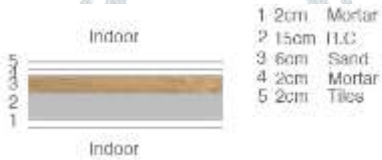


Figure 4.3-1 Occupancy weekday rate

5. Base case model simulation

The model simulation for the base case model is set according all the above building properties. The building envelope specifications are built upon the stated Table 2.1-1 and the model standards as in Table 0-1.The model is built to test the total energy consumption, The HVAC consumption for heating and cooling and the unmet hours. Table 5-1 shows the building construction of the following:

- Base case mode: Layers from outermost 2cm Mortar, 25cm Brick and 2 cm Mortar
- Code best practice: layers from outermost 2cm Mortar, 12cm Brick, 10cm Air Gap, 12cm Brick and 2 cm Mortar
- Proposed PCM construction: layers from outermost 2cm Mortar, 12cm Brick, 10cm Air Gap, 0.074 cm PCM M182/Q29, 12cm Brick

Code method	**Code best practice**	**Proposed PCM construction**
	External Walls	
		
R=0.8m^2.K/W	R=0.96m^2.K/W	R=0.96m^2.K/W -PCM:M182/Q29
	Roof	
		
R=3.15 m^2.K/W	R=3.15 m^2.K/W	R=3.15 m^2.K/W - PCM: M182/Q29
	Internal Ceiling for typical floors	
		
	R= 0.4 m^2.K/W	
Openings		Internal partitions
		
Guardian 8mm Float Glass– ARGON/AIR 90/10 20mm– Guardian 8mm Float Glass Float: Aluminum		R=0.22 m^2.K/W
U 2.577 - SHGC 0.396		

and 2 cm Mortar

The building settings in the three cases are similar. The difference is in the opaque building envelope. The base case holds the recommended sequence of construction according to the Egyptian Code to Improve Energy Efficiency. The Code best practice is a recommendation of the code for a better performance by adding an air gap. air gap has gained considerable importance in modern building design and construction. Essentially, the air layer serves as an extra layer of insulation or a ventilation route. The proposed PCM construction is set to add a PCM material to all opaque building envelope and the PCM allocation is adjusted as recommended by the literature review.

Table 5-1 Comparison of building envelope components through 3 different building construction methods

5.1. Base Case model Simulation results

The simulation results of Design Builder tool show a comparison between the three cases shown in Table 5.1-1. Figure 5.1-1 show the parallel coordinate plot for the three construction methods.

Table 5.1-1Simulation results comparison between Code method, Code best practice, Proposed PCM construction

	Code method	**Code best practice**	**Proposed PCM construction**
Total Site Energy KWh	844,111.13	104,2684.99	100,6896.53
HVAC Heating KWh	8,875.56	9,039.63	1,517.65

HVAC Cooling KWh	496,414.63	629,736.88	60,3465.18
HVAC Total KWh	505,290.19	638,776.51	604,982.83
Time Setpoint Not Met During Occupied Heating (300)	3.65	0	0
Time Setpoint Not Met During Occupied Cooling	14.15	1.25	0
Time Not Comfortable Based on Simple ASHRAE 55-2004	2098.6	1757.45	710.15

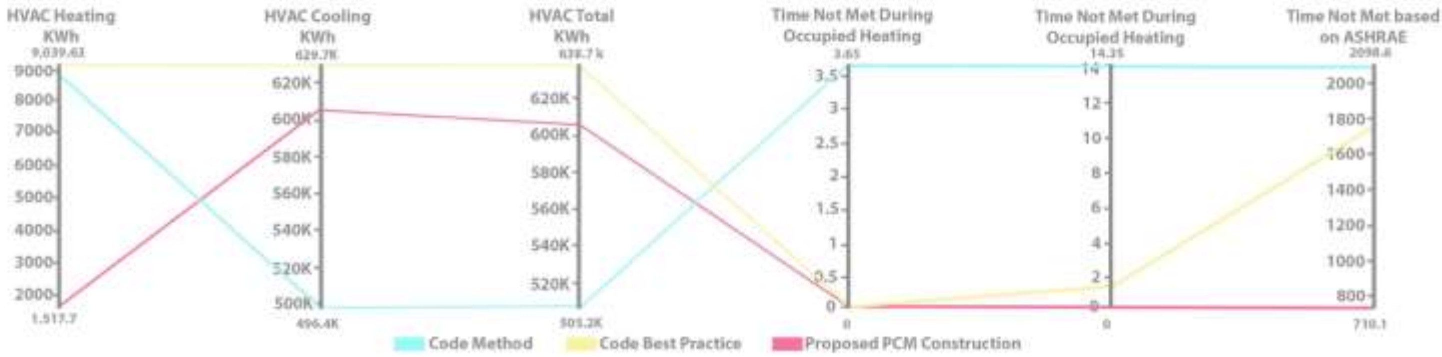


Figure 5.1-1 Comparison between the three-construction materials Code method, Code best practice and Proposed PCM construction

The code method construction showed the lowest cooling HVAC and a very high value of Time not comfortable according to ASHRAE. Code best practice showed the highest HVAC cooling and heating and high Time not comfortable based on simple ASHRAE. The proposed PCM construction showed the least HVAC heating and lowest Time not comfortable based on simple ASHRAE. Based on ASHRAE Calculation process for standard 90.1 2010 Performance using Performance Rating Model the Unmet Load Hour UMLH should not exceed 300. In this case all models UMLH is >300. Therefore, further simulation is required to modify building performance.

6. Building Envelope using PCM

This building uses the same base case model building with modified building envelope material, using PCM in different wall allocations. The building uses the same specifications of the medium office building simulated in the previous section. Adding to the building an air gap with upper opening to discharge extra heat and ventilate the PCM. The building uses the same building occupancy, lighting, plug loads and HVAC schedules same as the first simulation.

The allocation of PCM in building envelope is a debatable issue according to previous research, therefore different simulations are addressed to test the sensibility of the model to different PCM allocations.

The 4 models are set to compare HVAC consumption difference and all other model settings are set the same. The PCM used is M182/Q29 ,where M is the value of energy storage and Q is the melting point which is 29 ^{0}C. The building is set on four different building cross sections from the outermost to innermost compared to code best practice. The building envelope construction as follow:

- Base case according to the Egyptian code of construction: Layers 2cm Mortar, 25cm Brick and 2cm Mortar
- Case A: Layers from outermost 2cm Mortar, 12cm Brick, PCM M182/Q29, 10cm Air gap, 12cm Brick and 2cm Mortar
- Case B: Layers from outermost 2cm Mortar, 12cm Brick, 10cm Air gap, PCM M182/Q29, 12cm Brick and 2cm Mortar
- Case C: Layers from outermost 2cm Mortar, 12cm Brick, 10cm Air gap, Insulation, PCM M182/Q29, 12cm Brick and 2cm Mortar
- Case D: Layers from outermost 2cm Mortar, 12cm Brick, PCM M182/Q29, Insulation, 10cm Air gap, , 12cm Brick and 2cm Mortar

6.1. Building envelope using PCM simulation results

The model is used to test the base case model and the four other building envelope cross section to test the model sensitivity to PCM. As mentioned in section 3.2 the allocation of PCM has been debatable specially that the material has different properties that changes its phase with different temperature, therefore the allocation may depend from building to building and from climate to climate. Table 6.1-1 shows the comparison between best code practice simulation and 4 cases using PCM.

Table 6.1-1 Code best practice HVAC energy and time not met compared too case A,B,C and D

	Code best practice	**Case A**	**Case B**	**Case C**	**Case D**
Total Site Energy KWh	1042684.99	1012865.93	1006896.53	1015513.85	1008960.56
HVAC Heating KWh	9039.63	1634.44	1517.65	1391.86	1503.26
HVAC Cooling KWh	629736.88	609808.12	603465.18	612861.7	606033.93
HVAC Total KWh	638776.51	611442.56	604982.83	614253.56	607537.19
Time Setpoint Not Met During Occupied Heating (300)	0	0	0	0	0
Time Setpoint Not Met During Occupied Cooling	1.25	0	0	0	0
Time Not Comfortable Based on Simple ASHRAE 55-2004	1757.45	872.65	710.15	907.2	850.6

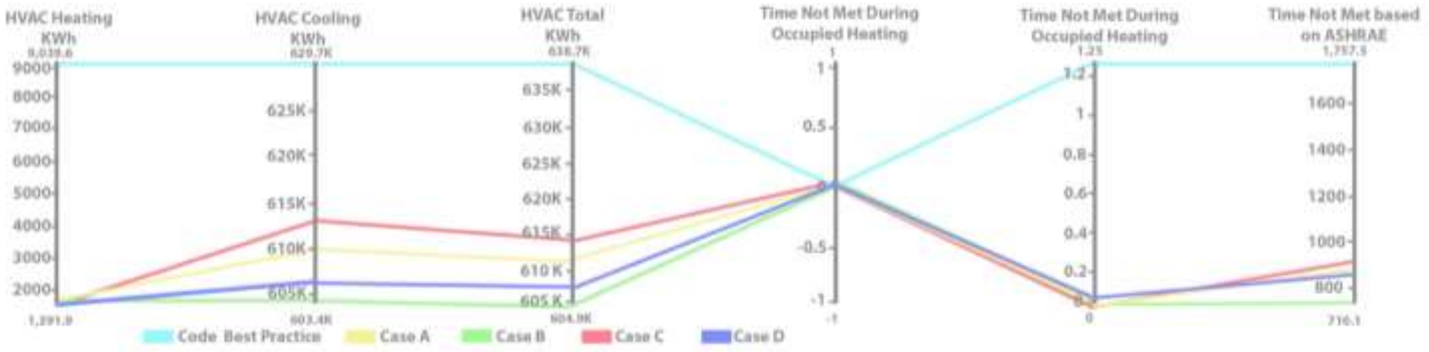


Figure 6.1-1 Comparison between code best practice and 4 PCM cases

The base case model showed heating and cooling loads on the whole building higher than the other PCM building envelope allocations used on the same model schedules and settings. **Case B** show the best material allocation among the other 3 cases. As the total HVAC consumption is the minimum among other cases and Time not comfortable according to ASHRAE. The result of the total HVAC energy used is less than code best practice by 10%. The Time Not Comfortable based on simple ASHRAE is less than the code best practice by 40%. Based on ASHRAE simulation standards and the UMLH is >300. Therefore, further simulation is required to modify building performance.

7. Building envelope using PCM with window shading simulation

Design builder simulation did not show the best performance according to ASHAE further model justification will be held to overcome the Time Not Comfortable Based on Simple ASHRAE 55-2004. After trying several factors of the building model options like increasing the building resistivity, changing some building envelope techniques and modifying schedules. The model showed a slight change in energy performance and Time Not Comfortable.

When compared to the overall building envelope, the glazing area has the lowest thermal resistance. In cold areas, lowering the heat transmission of windows is critical for reducing the heating demand of buildings. Since the model has a combined window design that makes the heat gain from the windows is very high. It is better to consider window shading.

7.1. Window shading

Window shading is a main factor tab that regulates how much heat enters the building through the windows. The model's windows transmit a lot of heat, which makes the unmet hours inside the building very high as shown in section 6.1 . By attaching window blinds to the windows, this can reduce the amount of heat that is transmitted inside the building and increase the envelope's resistance.

Design builder has 4 window shade types:

- Slat
- Shade

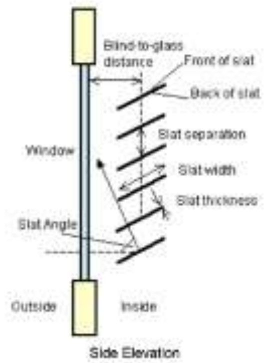


Figure 7.1-1 Internal Slat [24]

Transparent insulation (a blind of this category the position must be 'Switchable'.

Slat is a type of window blind that is made up of flat slats that are all the same size and spacing. It is unlike window shade, which act as a perfect diffuser in modeling. The visible and solar transmission and reflection properties of window blinds are highly influenced by the angle of slats and the angle of incidence of solar radiation. When it is in use, the dividers cover the whole window area without covering the window frame. The window's blind is aligned with the glazing location. The window is not covered when the blinds are retracted. The slat angle is the angle formed by the glazing and the slat's outer surface as seen in **Error! Reference source not found.**. The x axis is set to be horizontal to the window at 0 degrees, and the y axis is set to be vertical at 90 degrees [24].Blinds with high reflectivity slants from the indoor side with the same operating schedules as the building are chosen as the shading method.

7.2. Building envelope using PCM with window shading simulation result

The simulation comparison in this part selected the best case using PCM, case B with lower vents and the same case adding window blinds. This is to monitor the difference in HVAC consumption when limiting the heat gain coming from the transparent building envelope.

Table 7.2-1 Case B with lower vents HVAC energy and time not met compared too case B with lower vents & window blind

	Case B	**Case B with window blind**
Total Site Energy KWh	1007517.66	995373.32
HVAC Heating KWh	1458.53	1597.3
HVAC Cooling KWh	604145.42	591862.31
HVAC Total KWh	605603.95	593459.61
Time Setpoint Not Met During Occupied Heating	0	0
Time Setpoint Not Met During Occupied Cooling	0	0
Time Not Comfortable Based on Simple ASHRAE 55-2004	711.8	19.95

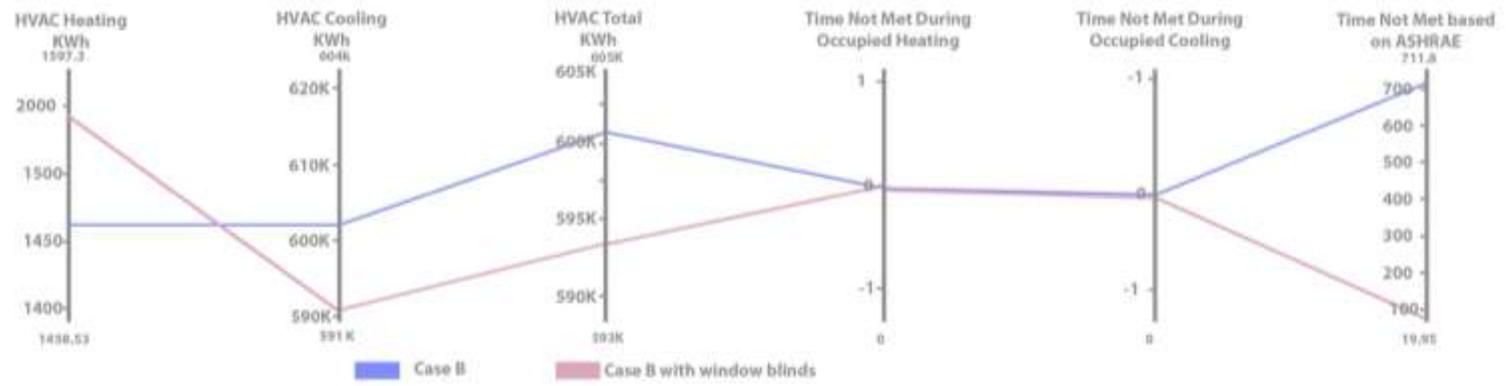


Figure 7.2-1 Comparison between Case B and Case B with window blind

Case B with window blind showed a bit higher heating HVAC consumption and total HVAC energy consumed is less than Case B. The time not met according to ASHRAE showed a major decrease in energy consumption as shown in Figure 7.2-1. As the building envelope cannot be treated a s opaque only without essential elements to add. The transparent building envelope has a major effect on the building and window blinds is essential as in real life. According to Table 7.2-1and the ASHREA standards of simulation the total unmet hours <300 in all cases. This makes the model using PCM in the internal part of airgap using window blind is the best simulated result.

8. Conclusion

The model is generated on Design builder as a medium office building according to ASHRAE building simulation standards. The building is set to be in Cairo following the Egyptian code to improve building energy efficiency. The model simulation is set to test the HVAC consumption upon different building envelope materials. **The base case building envelope** is designed by the **design builder** according to the **Egyptian code**. The other tested building envelope is also based on the Egyptian code materials of **exterior envelope adding Phase Change Material** with different **allocations** to test the difference in **HVAC consumption** and how it affects the building.

The model is sensitive to the used materials and the total HVAC energy for the building is reduced after adding the PCM. The HVAC energy is reduced in heating and cooling with PCM. The allocation of PCM and the air gap showed a direct impact on the building energy consumption. Locating window blinds on transparent building envelopes is a must to reduce heat gain through windows.

Acknowledgment

All praise and thanks be to Allah, the Most Gracious and the Most Merciful.

I would like to express my special thanks to the Department of Architectural Engineering in Faculty of Engineering, British University in Egypt. I am thankful from the depth of my heart to my Supervisors, Prof. Khaled Dewidar, Prof. Mostafa Refaat, Dr. Ashraf Nessim and Dr. Ali Abdelhalim for being so generous to me, with their time, patience, advice and valuable opinion that's lead to the completion of this research. My thanks are further extended to my beloved family and all my friends I care to name.

I would like to express my deepest gratitude to my father, for his persistent push, my mother, for being always loving and comprehending, my husband for his endless support. I dedicate this research to all of them.

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